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Optimal Sizing of Behind-the-Meter Energy Storage with Stochastic Load and PV Generation for Islanded Operation

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Abstract

Energy storage systems are flexible resources that accommodate and mitigate variability and uncertainty in load and generation of modern power systems. We present a stochastic optimization approach for sizing and scheduling a behind-the-meter energy storage system (ESS) with a solar photovoltaic (PV) system and a generator in islanded operation for balancing a critical load.

Problem Formulation

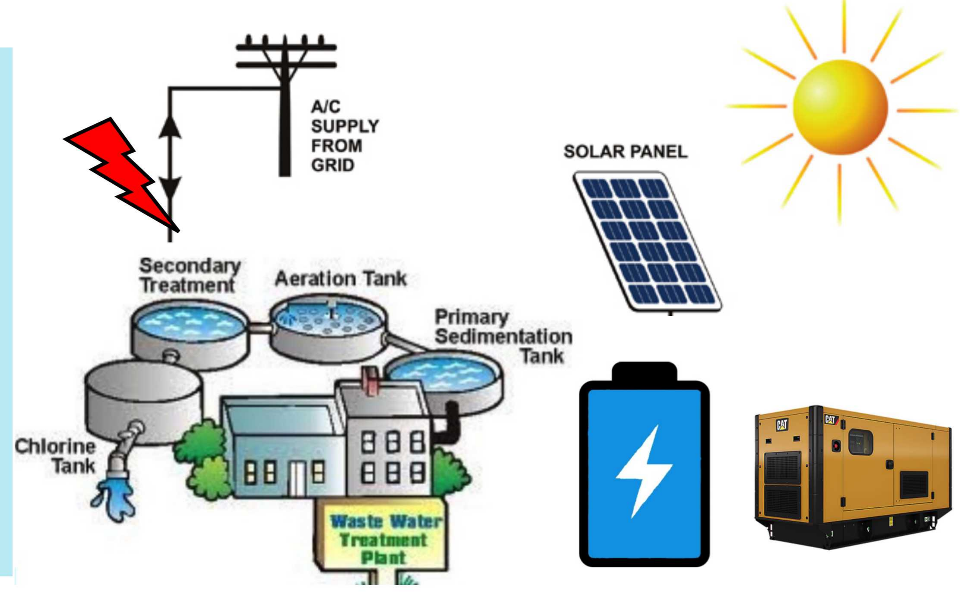
Energy storage model $S_{t+1} = \gamma_s S_t + \gamma_c h P_t^c - h P_t^d$

PV generation model $P_t^{\mathrm{PV}} = \gamma_{\mathrm{PV}} \gamma_{\mathrm{conv}} A_{\mathrm{PV}} \phi_t$

Forecasts
$$\begin{cases} P_t^{\mathrm{load}} = \hat{P}_t^{\mathrm{load}} + \Delta P_t^{\mathrm{load}} \\ P_t^{\mathrm{PV}} = \hat{P}_t^{\mathrm{PV}} + \Delta P_t^{\mathrm{PV}} \end{cases}$$

Net load $P_t^{\mathrm{net}} = P_t^{\mathrm{load}} - P_t^{\mathrm{PV}}$

Load balancing $P_t^{\mathrm{balance}} = P_t^{\mathrm{net}} + P_t^c - P_t^d - P_t^g$



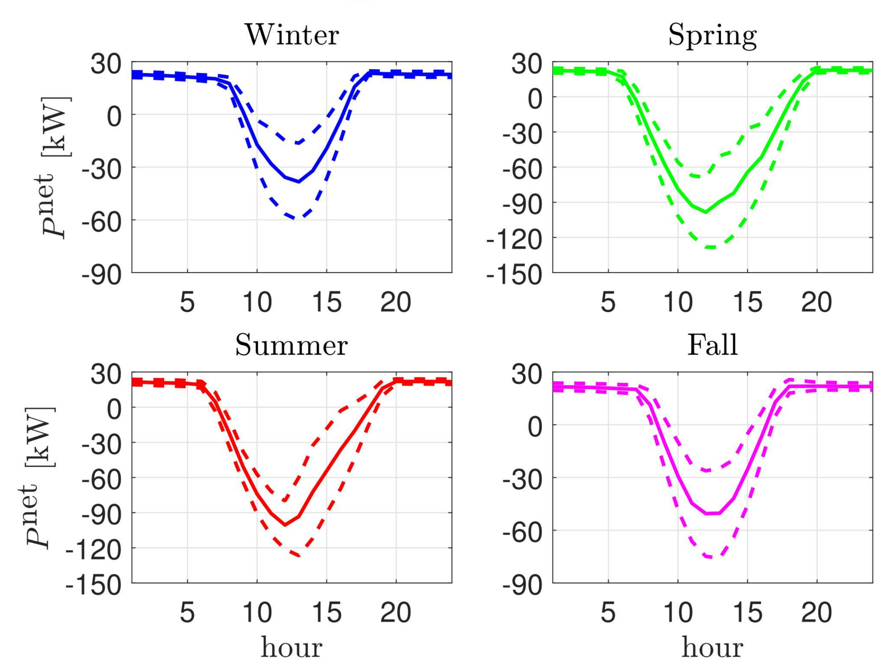


Fig. 1. Hourly mean and standard deviation of Pnet for each season. The mean is shown with a solid line, and the standard deviation envelope is shown with dashed lines.

Stochastic Optimization

$$\min_{\mathbf{P}^c, \mathbf{P}^d, \mathbf{P}^g} \quad w_1 \overline{S}_{\mathrm{ESS}} + w_2 \overline{S}_{\mathrm{gen}}$$

Subject to the following constraints:

Energy capacities:
$$\overline{S}_{\mathrm{ESS}} \geq 0$$
$$h \sum_{t=1}^{T} P_t^g \leq \overline{S}_{\mathrm{gen}}$$

Charge/discharge commands:
$$P_t^c \geq 0$$
$$P_t^d \geq 0$$

Power ratings:
$$P_t^c + P_t^d \leq \overline{P}_{\mathrm{ESS}}$$
$$0 \leq P_t^g \leq \overline{P}_{\mathrm{gen}}$$

SOC constraint:
$$0 \leq \gamma_s S_t + \gamma_c h P_t^c - h P_t^d \leq \overline{S}_{\mathrm{ESS}}$$

Probabilistic load balancing constraint
$$\mathbb{P}\{P_t^{\mathrm{net}} + P_t^c - P_t^d - P_t^g \leq 0\} \geq \alpha$$

If forecast errors have zero-mean normal distributions, probabilistic load balancing constraint can be written as
$$P_t^d + P_t^g - P_t^c \geq \sqrt{2} \Delta P_t^{\mathrm{net}} \times \mathrm{erf}^{-1}(2\alpha - 1) + \hat{P}_t^{\mathrm{net}}$$

Case Study

- Grid contingency causes resources at a water treatment plant to be islanded for one week.
- Resources include an ESS, PV system, and generator.
- Determine minimum required energy capacity.
- Schedule generator and charging/discharging of ESS to balance critical load.
- Load and global horizontal irradiance (GHI) data from a water treatment plant in New Mexico, USA available from June 2015 to June 2017.
- Fit normal distributions to historical data for each hour in day and each of the four seasons, resulting in 96 different distributions.
- Mean and standard deviations of distributions provide statistics for forecasts.

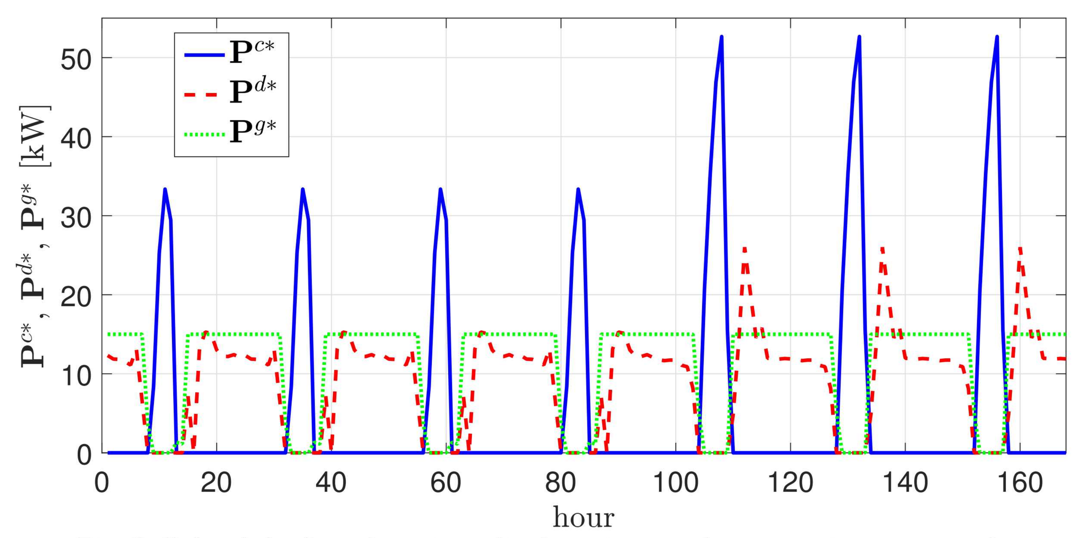


Fig. 2. Schedule for charging, discharging, and generating power from May 28 to June 3, 2016.

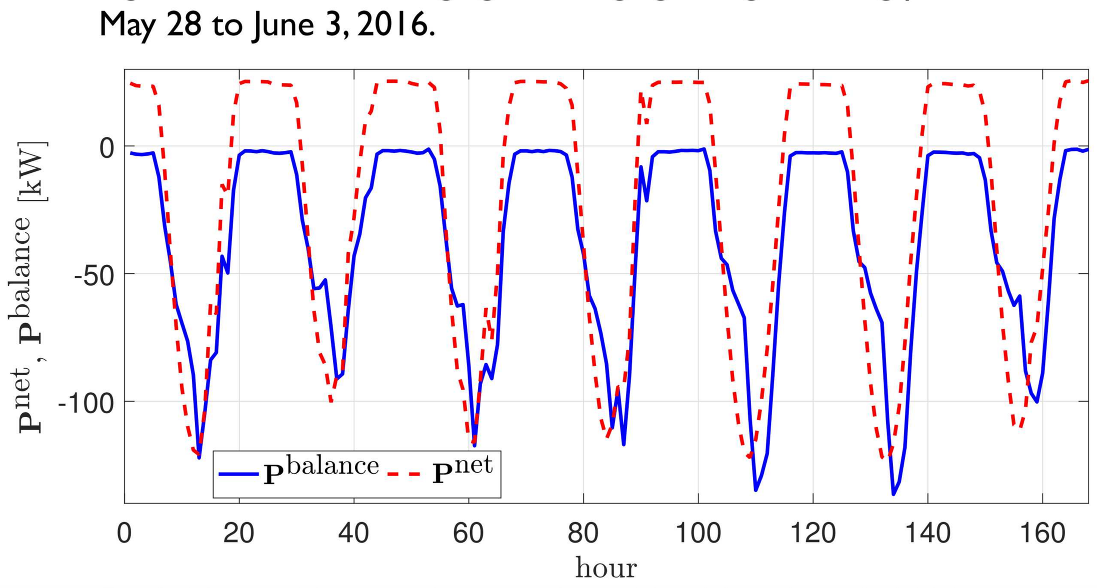


Fig. 3. Net and balanced power from May 28 to June 3, 2016 using true load and PV generation and the schedule for charging, discharging, and generating shown in Figure 2.

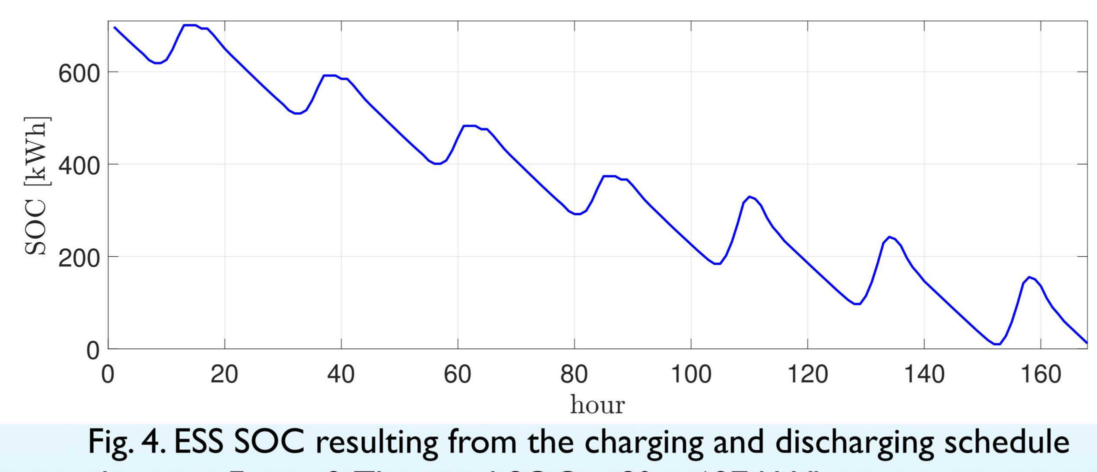


Fig. 4. ESS SOC resulting from the charging and discharging schedule shown in Figure 2. The initial SOC is S0 = 697 kWh.

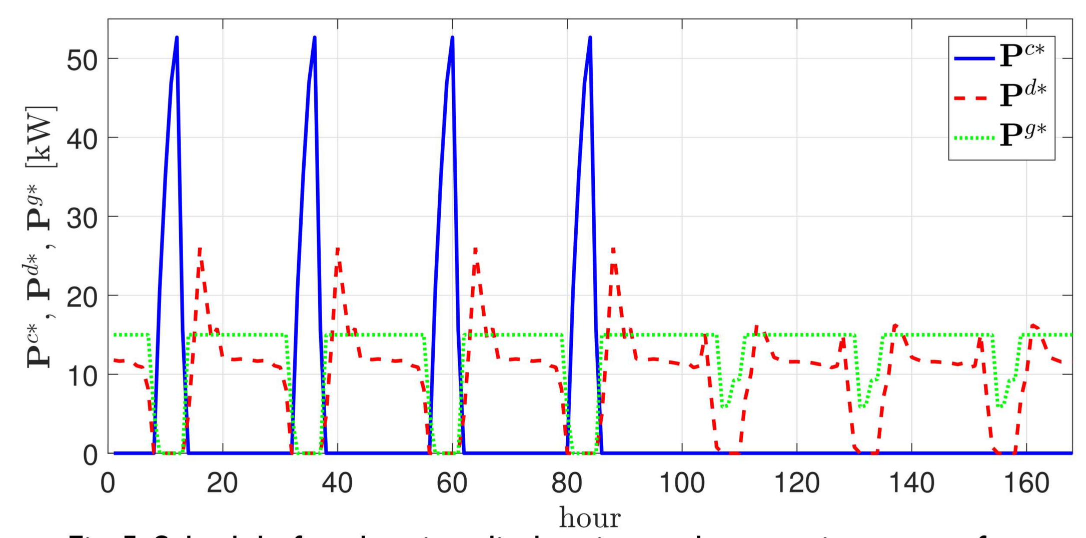


Fig. 5. Schedule for charging, discharging, and generating power from August 28 to September 3, 2016.

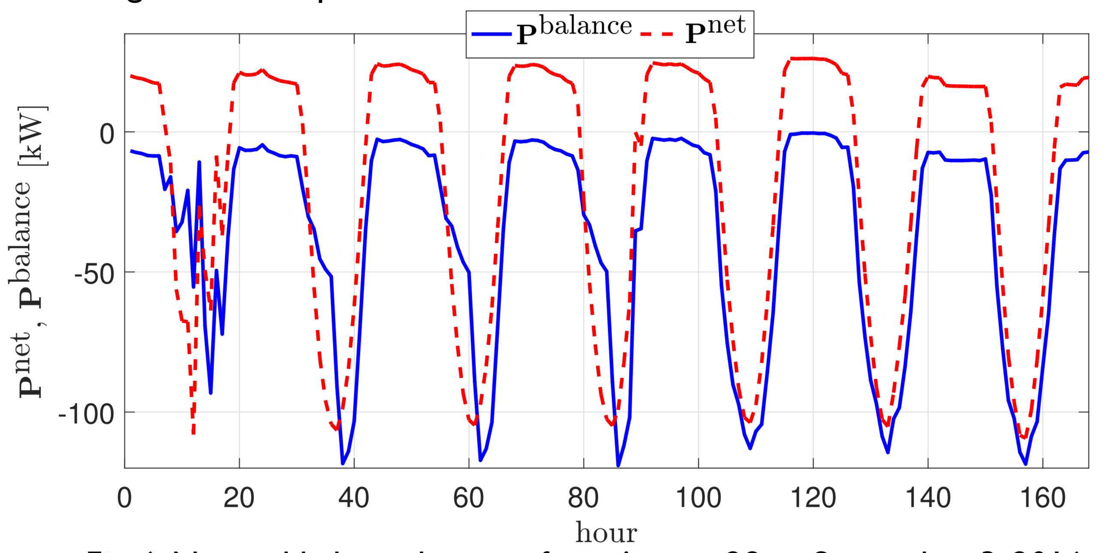


Fig. 6. Net and balanced power from August 28 to September 3, 2016 using true load and PV generation and the schedule for charging, discharging, and generating shown in Figure 5.

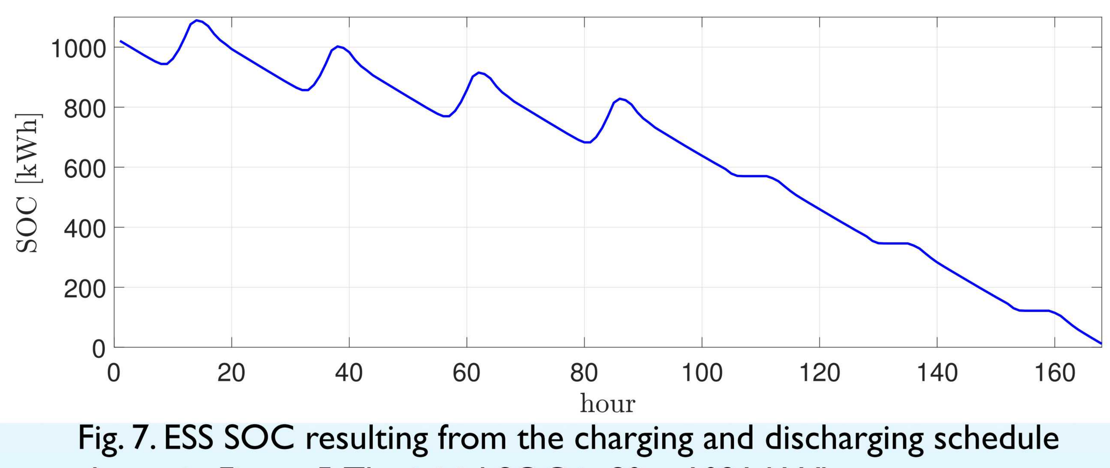


Fig. 7. ESS SOC resulting from the charging and discharging schedule shown in Figure 5. The initial SOC is S0 = 1021 kWh.

Parameters

Parameter	Description	Value	Units
h	Time step	1	hour
γ_{PV}	PV panel efficiency	0.15	-
γ_{conv}	PV conversion efficiency	0.90	-
γ_s	ESS storage efficiency	1.00	-
γ_c	ESS charging efficiency	0.85	-
A_{PV}	Total area of solar panels	1000	m^2
$\overline{P}_{\mathrm{ESS}}$	ESS power rating	150	kW
$\overline{P}_{\mathrm{gen}}$	Generator power rating	15	kW
S_0	Initial SOC	$0.8\overline{S}_{\mathrm{ESS}}$	kWh
w_1	Weight on $\overline{S}_{\mathrm{ESS}}$	1	-
w_2	Weight on $\overline{S}_{\mathrm{gen}}$	1.1	-
T	Optimization horizon	168	hours
α	Desired fraction of time critical load is met	0.99	-

Results

	May 28 - June 3	August 28 - September 3
$\overline{S}^*_{\mathrm{ESS}}$	871 kWh	1276 kWh
$\overline{S}^*_{\mathrm{gen}}$	1870 kWh	2092 kWh

Conclusions

- Proposed stochastic optimization for sizing and scheduling behind-the-meter energy storage.
- With normally distributed forecasting errors, probabilistic constraint can be reformulated as a linear inequality constraint, and optimization problem becomes a linear program.
- Case study: Reasonably-sized energy storage system, when optimally scheduled with the generator, successfully balanced critical load with naive forecasts of stochastic load and PV generation.
- Smaller energy storage may be used times of year when PV generation is higher relative to critical load, such as Spring and Summer.

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